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by Eric Kathe, Stephen Wilkerson, Alexander Zielinski, and Amr Baz

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Gun Structural Dynamic Considerations for Near-Target Performance of Hypervelocity Launchers

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Abstract

In many settings, especially urban warfare, targets may be anticipated to occur very near the weapon platform, or behind concrete walls, much to the hindrance of missiles. Direct guns offer distinct advantages for near-target threats. Nonetheless, both accuracy and performance of long rod penetrators are affected by out-of-plane velocities as well as initial yaw and pitch rates for conventional antitank systems. These components are driven, in part, by the exit conditions of a projectile upon discharge from the launcher. By ignoring cost, logistics, and current technology limitations, these exit conditions may be corrected by smart projectiles, provided the duration of flight is sufficient in length for corrective action. Still, this luxury may not be permissible for near-target performance. It is therefore important in gun design to consider the structural dynamic performance of the launcher system to help mitigate pointing error and angular momentum of rounds upon shot exit. It is the purpose of this report to present emerging technologies relevant to the structural dynamic performance of guns, electromagnetic (EM) or otherwise.

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1. Introduction

Kinetic energy (KE) weapons offer a number of advantages over more sophisticated weaponry such as missiles. First and foremost, they are extremely inexpensive, in cost and logistics, by comparison to missiles. Additionally, they are technically simple and very reliable. Basically, in principle, they are the same as shooting a hand-held rifle. A suitable definition for a KE weapon is "a weapon that imparts most of the weapon energy accelerating the round from the launcher." The projectile then damages or destroys the target through impact.* Using this definition, a broad range of weapons may be categorized as guns, including recoilless rifles, mortars, and direct and indirect fire cannons. Nonetheless, guns offer inexpensive solutions for many scenarios, including close combat engagements.

Current technology employs a wide variety of mechanisms to defeat armor. Principal among these are KE penetrators, as typified by the M829 series of ammunition currently used by the M1A fleet with the 120-mm M256 cannon (see Figure 1). Several underlying factors, which include impact velocity, penetrator mass, incident yaw (straightness of impact), and accuracy are the key to the penetrator's performance Typical engineering design solutions improve one parameter's performance, while damaging another's. To no surprise, as the first two parameters listed previously improve, the second two suffer. The impact KE is driven by the exit velocity of the round from the gun minus the integral effect of drag over the duration of the flight. Greater exit KE is achieved by increasing the integral of launch force pressure times bore diameter for gas guns and/or extending the distance over which the pressure is exerted on the projectile. This is true for conventional propellant-driven systems as well as electromagnetic (EM) guns.

The initial yaw and pitch and yaw and pitch rates are driven in large part by the mechanical disengagement of the round upon shot exit from the gun system (often called "kick-off") and are

* Of course, guns are also used to launch shells with high-explosive (HE) energy, and extended range munitions as well.

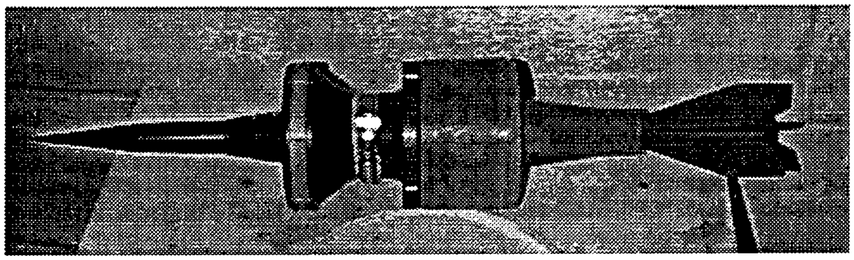

Figure 1. M829 KE Projectile.

damped out during the round's flight by the fins and their associated aerodynamic drag, provided the duration of flight is long enough. The greater the dynamic activity at kick-off, the further the projectile must fly prior to attaining an acceptable impact yaw and pitch or the larger the fins must be. The drivers of these undesirable dynamics are exacerbated by increased launcher length and in-bore projectile velocities, which often results in increased dynamic activity. Future smart rounds may increase the accuracy envelope but are unlikely to hasten the damping of penetrator yaw during early flight. Put simply, current and future penetrators are subject to poor performance for targets that are too near the weapon platform and this performance degrades further as length increases and bending stiffness is decreased.

Of course, these dynamic considerations are also important for EM guns. Because of the absence of propellant gas, the opportunity exists for EM guns to experience reduced muzzle motion. However, in-bore conditions, such as transitioned armature contacts, may overwhelm the dynamics offered by the gun structure alone. As with conventional guns, EM guns possess a deviation from the centerline (i.e., straightness). To date, there has been no program to address manufacturing issues of EM guns relevant to the centerline. In recent tests [1], the centerline profile is suspected to cause the large angular rates measured downrange (see Figure 2). These rates, in turn, then produce a deviation from the projectile's trajectory. This is called "aerodynamic jump" and has been shown to significantly degrade the subprojectile's dispersion. Recoil can also be reduced in an EM gun due to the absence of propellant gas. However, only limited tests have been performed [2].

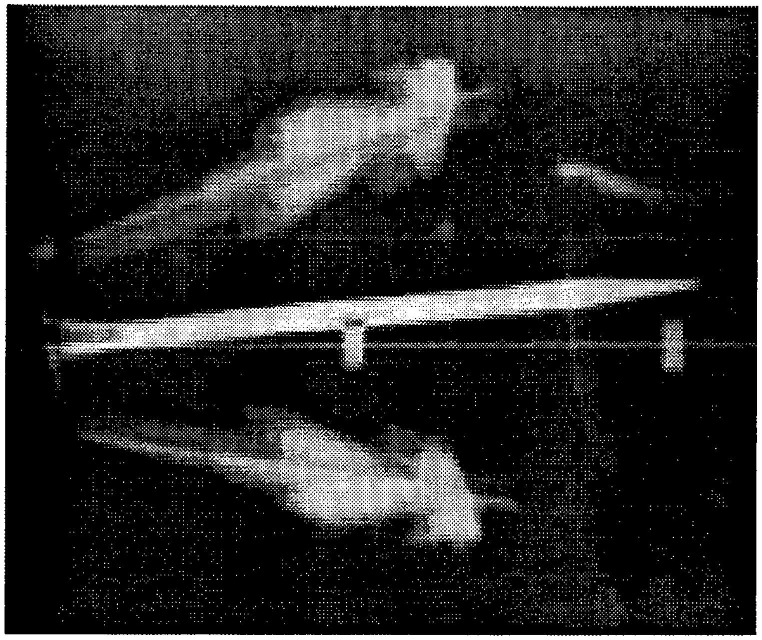

Figure 2. Initial Yaw of the EM KE Bullet Near Muzzle Exit.

While much focus is correctly placed on distant targets for future combat systems, it is equally important that the near-target performance of these systems be included in the systems analysis and integration phase of development. Thus, the cause of projectile yaw and pitch needs to be attenuated to reduce the dissatisfying compromise alternatives between near-target performance and fin drag contributions to range limitations. This is especially true for urban warfare scenarios where a target-rich environment may occur well within a kilometer of the weapon platform. Many design requirements for future launch packages exacerbate launch dynamics. Principally, faster rounds that require longer launchers will result in increased sensitivity to structural vibration. Nonetheless, higher velocity rounds increase the in-bore dynamic loading. This is due, in part, to the tube's deviation from straightness, which is typically proportional to the tube's length. It is also dependent on the dynamics caused by the recoiling motion of the gun system and the motion of the platform (i.e., a tank on the move). In either case, the greater the tube length, the more energetic the dynamic path the bullet must travel during launch. Coupling this with the demand to reduce the weight of the overall weapon platform, while adding projectile length and flexibility, the need to incorporate structural dynamic enhancement technology is vital to the in-field success of any future gun-based launch system. This is true for both near-target performance and accuracy at extended range.

2. The Basics of Gun Dynamics

All guns, in order to concentrate the impetus force upon the KE of the projectile, constrain the projectile to follow the centerline of the gun, which is subject to static and dynamic deformation. All gun systems must satisfy Newton's third law. That is, the center of mass of the gun-projectile system must remain constant under internal launch loads. Thus, the gun itself will be subject to significant acceleration opposite in direction to the launch. For current tank guns, 500 g's is a typical peak recoil acceleration. Recoilless guns eliminate gun recoil by ejecting momentum carrying inertia out the back of the system that balances the forward momentum of the projectile. Physically, there are no means to enable a one-way momentum discharge of any launcher regardless of the method of propulsion.*

Over the duration of launch, these gun-projectile interaction loads exacerbate any preexisting deformation of the barrel centerline and its initial conditions. Thus, these initial conditions, in addition to the launch loads, drive the state-dependent differential equations that govern launch dynamics. Not surprisingly, higher launch velocities increase the off axis loading magnitudes, and longer launch duration increases the time available for dynamic deformation of the bore centerline due to recoil. The initial conditions of launch may be broken down into two distinct contributions:

- Static Curvature: Caused by imperfect manufacturing tolerances,† gravity droop, and nearly static causes, such as thermal deformation caused by uneven temperature distribution.

- Dynamic Curvature: Caused by environmentally induced vibrations. Such vibrations are induced while the weapon platform traverses rough terrain.‡

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* A more complete treatment of launch-induced loading of guns was presented at the 8th EML (EML96).

† The machining of a gun tube's inside bore is never perfectly straight or circular due to the limitations and precision of the tools used to cut the bore.

‡ Other sources include the feedback controller that holds the gun on target clearances between parts and the like, which can lead to tube motion.

3. Control of Gun Dynamics

The control of the launch dynamics that contribute to kick-off can be achieved using three loosely categorized approaches:

- Parametric design of the launcher to be less receptive to launch-induced deformation loading. For instance, a stiffer and/or heavier gun, and recoil mount design considerations.

- Active and passive control of the initial conditions of the launcher centerline.

- Active and passive control of launcher flexure during launch dynamics.

3.1 Parametric Design. Major strides have been made in the past two decades that have increased the understanding of the dominate launch loads and thus the principal design issues of gun systems. Notable among the design lessons-learned are: maintain a coincident bore centerline and distributed launcher center of mass; decouple recoil path constraint from the bore dilation of gas guns (the analogy to coil gun and rail gun "magnetic pressures" is direct). Also, design tradeoffs upon the timing of shot ejection and the bore centerline deflection motion, commonly called gun whip, have been undertaken. The design of gun systems to discharge at a favorable muzzle-end deflection "phase" is hampered by the need to fire rounds with dramatic variation in launch speed, etc. Thus, a design that may be well timed for one round may be poorly timed for another. EM guns are prone to suffer additional challenge to the nonisotropic behavior of the composite construction utilized. Gas guns that are designed to withstand internal pressure also contributed toward increased cross-sectional beam stiffness. The emphasis placed upon the hoop integrity of rail launchers does not contribute in-kind to lateral rigidity. It would be a misnomer to consider this parametric design category a mature technology. Extension of the capabilities of guns and extreme emphasis on reduced weight are leading designs into uncharted waters. Design for favorable flexure may soon usurp design for stiffness.

3.2 Control of Initial Conditions. Control of centerline initial conditions begins with static contributions. First, emphasis must be placed on manufacturing methods. Second, the effects of gravity deformation may be addressed. Currently, gravity droop is not completely canceled by an intentional manufactured bend to oppose the droop. Note that many launchers are subject to a wide variation in elevation; the effective lateral load imparted by gravity is elevation dependent. For several decades, the effects of uneven barrel heating have been quantified, and thermal shrouds are now incorporated on most large-caliber weapons. The potential for active control of static curvature has been demonstrated using intentionally applied temperature gradients to gun systems [3]. Embedded piezoelectric fiber composites may also prove promising for future structural applications [4], although there has been no known application to gun systems as of yet.

Control of dynamic initial conditions shows tremendous promise as a means to design a launcher that has desirable dynamic performance, both in-bore and upon shot exit. It is worthy to note that the lateral loads imposed upon the gun/projectile interface throughout the in-bore dynamics are substantial and are becoming more of an influence of sabot design. The failure of rotating bands on extended length artillery cannons currently in development is resulting in high levels of muzzle-end wear and reduced weapon performance. Primary in the control of dynamic initial conditions is to arrive at the conditions desired. Current limitations on ignition repeatability impair the ability to establish a desired dynamic initial condition. Put simply, although a numerical model of the gun dynamics can be back propagated from a desirable exit condition to the required initial conditions, the variation in shot-start pressure timing is of concern. This provides significant motivation to the development of electrically controlled ignition for chemical propulsion guns. The drawback is compounded by the delay time that may be required to achieve the desired condition. A simple example would be to dynamically cancel gravity droop of a launcher by wiggling it straight using the existing elevation mechanism immediately prior to launch. For these reasons, the objective functions for control of dynamic initial conditions are currently to quiet any existing disturbance from the static deflection. Thus, by reducing the variation in initial conditions, the repeatability of the launch dynamics achieved via parametric design or control of static initial conditions is increased.

Case studies are later presented to demonstrate control of initial conditions: a vibration absorber, active constrained layer damping, and the effect of initial conditions to projectile kick-off.

3.3 Control During In-Bore Launch. Control of launcher flexure during in-bore dynamics is challenging due to the brief time-window available to effect a desirable response. EM guns offer a potential benefit, since the in-bore acceleration profile is directly proportional to the current and magnetic field. These initial conditions can be controlled for a submillisecond regime unlike in a conventional gun; no pressure gradient (no gas products) exists in an EM gun. The bandwidth of many large-scale structural actuators is so long that half of the launch may take place prior to the first corrective response. Most notable of the efforts undertaken in this category is the smart barrel actuator effort.* The goals of that program were to maintain control of gun tube dynamic conditions. The power requirement is a major issue, since the bending energy must be applied in a particularly brief period of time. The formulation of a control law that works in synergy with the anticipated gun dynamic flexure holds greater promise than merely attempting to hold the muzzle of the gun straight. However, such a control law requires the development of nonlinear observers to best ascertain the state of the system in real-time.

4. Initial Conditions of KE Rounds at Muzzle Exit

The dynamic state of a KE projectile at shot exit contributes to the effectiveness and accuracy of the weapon. The less off-axis disturbances observed in the bullet's trajectory, the better its performance and the better its accuracy. Off-axis disturbances influence the sabot's aerodynamic liftoff, decreasing accuracy. On the other hand, high initial yaw reduces effectiveness at close range and high yaw rates are believed to be equally important [5]. Three-dimensional finite element models have been developed to help predict the effect of design changes to gun and bullet systems. These have been used effectively to aid researchers in the design and analysis of conventional gun

* Mike Mitice, DPO (AMSTA-AR-FSF-R), U.S. Army Armament Research, Development, and Engineering Center (ARDEC), Picatinny Arsenal, NJ.

bullet systems [6, 7]. However, bullet design alone may not be sufficient in mitigating KE bullet exit state conditions.

A study comparing the M865 and M829A2 bullet exit state conditions was initiated using three-dimensional finite element techniques. Figure 3 shows the finite element model of the M829A2 bullet. The M865 KE bullet model used similar detail.

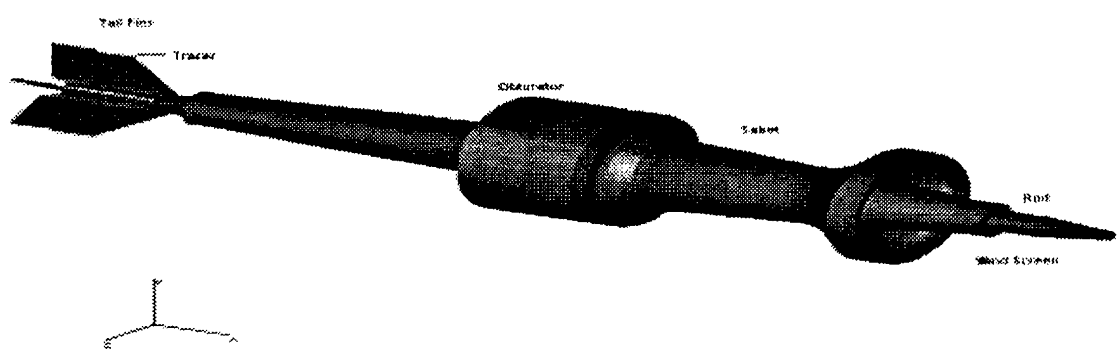


Figure 3. Finite Element Model of the M829A2 KE Projectile.

The model includes three individual sabot petals, a heavy metal rod, the threaded region, a wind screen, tail fins, a tracer, and an obturator. The front and rear bore riders have sliding interfaces that force the projectile to follow the nonstraight tube profile and tube motion as the gun recoils during the simulation. The rear of the projectile is pressurized using an XKTC-Nova interior ballistic simulation for the pressure versus time [8]. The gun system is equivalently sophisticated in detail and is shown in Figure 4.

The gun system model parts include the gun tube, piston, thrust-king-nut assembly, cradle, mantlet, breech, and elevation mechanism. The gun tube is pressurized in using the data from the XKTC simulation and has sliding interfaces and gaps between recoiling parts. The tube has been shown to recoil and exhibit similar dynamic motion as the actual system. A simulation of the

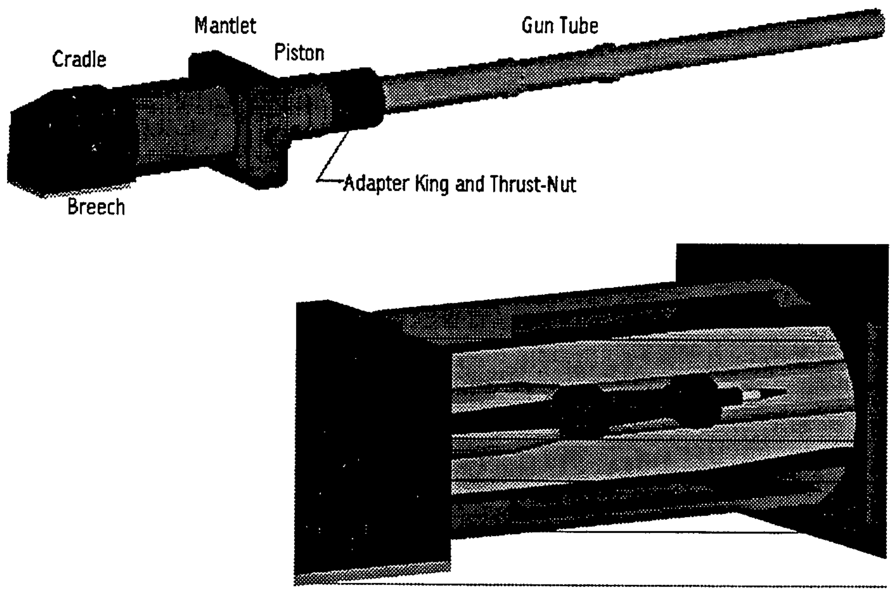


Figure 4. Finite Model of the M256 Gun System and Recoil.

conventional 120-mm M865 and M829A2 bullets from two different gun tube shapes and the resulting exit state conditions are given in Table 1.

Table 1. Pitch and Yaw and Angular Rates as Calculated by Transient Finite Element Simulation

	M865 G/T 4087	M865 G/T 5064	M829A2 G/T 4087	M829A2 G/T 5064
Vertical Velocity (in/s)	-128	16	-46	0.6
Horizontal Velocity (in/s)	59	88	23	45
Pitch Rate (rad/s)	6.2	6	-1.5	-3
Yaw Rate (rad/s)	-6	-5	-4.3	2

The velocities are given in inches per second, and the rates are given in radians per second. The gun tube serial numbers for M256 120-mm guns are referenced. Tube profile measurements were obtained from the manufacturing inspection records at Watervliet Arsenal, Watervliet, NY.

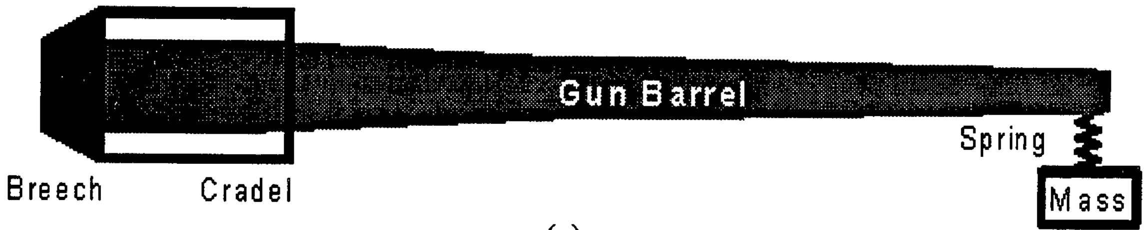
5. Reduced Dynamic Initial Conditions Case Studies

Two methods of structural control that are wholly or essentially passive in nature (not using external power to actively control launcher shape) have been investigated to determine their ability to attenuate dynamic initial conditions and subsequently decrease variation in projectile kick-off. Active control, using the stabilization system, has been investigated by other researchers [9, 10].

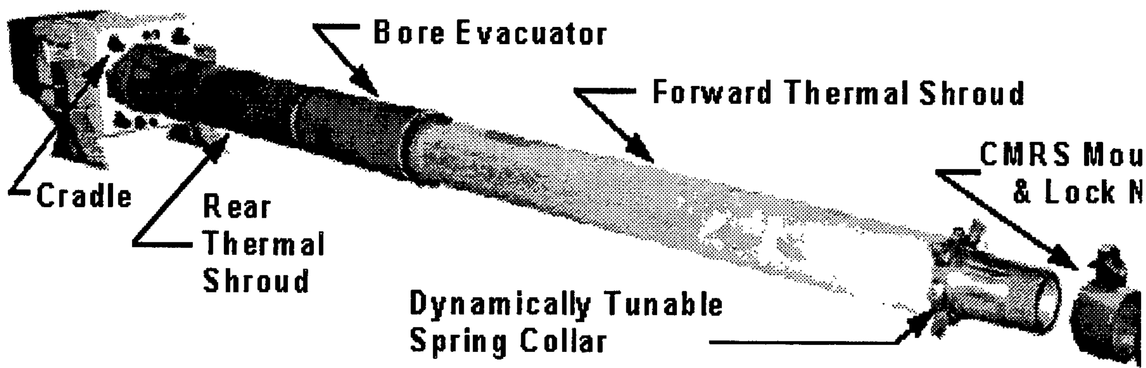
• A Muzzle End Vibration Absorber: A damped vibration absorber consists of a tuned mass spring dash-pot system that is coupled to a vibrating structure at locations of undesirable vibrational activity, Figure 5a. The effect of the absorber is to introduce a complex conjugate pole-zero pair to the transfer function of the original structure. Placement of the new pole-zero pair near to the pole that constitutes the troublesome vibrational activity, by tuning the spring and dash-pot coefficients, shifts the frequency away from the new pole. The zero introduces a notch filter effect that diminishes with increased damping as does the magnitude of response for the two adjacent poles. Thus the original system may be altered such that its original mode is replaced by two modes of reduced magnitude [11, 12].

Such an absorber has been applied to an extended-length 120-mm gun barrel mounted to a modified M1A1 battle tank, Figure 5b. The results of nonfiring bump-course testing have demonstrated a significant reduction in barrel flexure of the principal structural mode of vibration [13, 14]. Thus the dynamic initial conditions for launch have been successfully attenuated using a simple passive device. A rugged test fixture for live fire evaluation will be completed by the end of FY 98. The bump-course power spectra demonstrate the dramatic reduction of vibrational energy at the first fundamental frequency of the gun system, near 18 Hz (Figure 6). The low-frequency response, near 2 Hz, is caused by the fundamental of the tank hull upon its suspension. Attenuation

of this low frequency was not the design objective of the low-amplitude, lightweight muzzle end absorber.



(a)



(b)

Figure 5. A Schematic of a Simple Muzzle End Vibration Absorber (a) and a Photo of the Test Fixture (b).

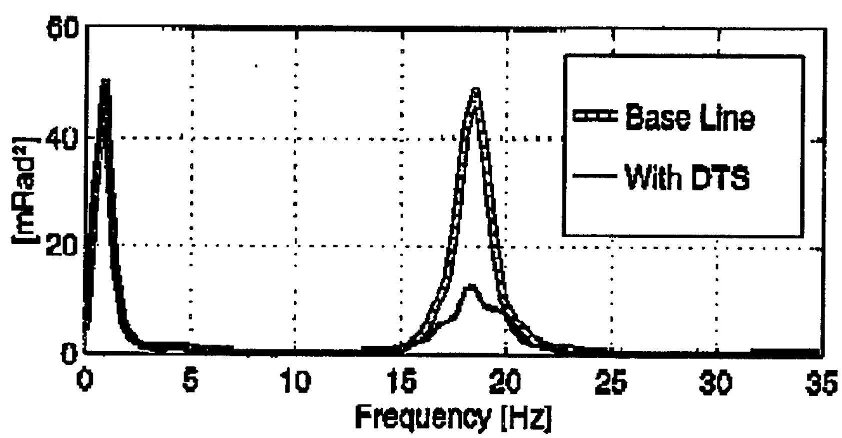


Figure 6. Juxtaposed Vertical Barrel Bending Spectra for Bump Course Runs Conducted at the U.S. Army Aberdeen Test Center (ATC), Aberdeen Proving Ground, MD.

The effects of the vibration absorber during launch are not expected to enhance the launch dynamics. Tuned for the first fundamental frequency, the absorber is essentially decoupled from the high-frequency dynamics.

• Active Constrained Layer Damping (ACLD): ACLD constitutes a method of structural control that enhances the dissipation of undesirable vibrational energy into a viscoelastic layer by the use of an active control of shear strain distribution that uses little external power. Thus, although the method utilizes a small power supply, the vast majority of the structural dynamic energy is dissipated, not canceled, by a counteracting active applied moment.

Figure 7 shows a schematic drawing of a flexible gun barrel subjected to an internally moving load f_d traveling along its longitudinal axis. The barrel is treated with an ACLD treatment that consists of a viscoelastic damping layer sandwiched between two piezoelectric films. The first film that is bonded to the barrel acts as a sensor generating a voltage V_s proportional to the barrel transverse deflection. The second film is bonded to the viscoelastic layer in order to passively constrain its motion relative to the tube, and when activated by a control voltage V_c, it acts as an actuator that enhances the shear strain of the viscoelastic layer. With appropriate control law, it would be possible to considerably increase the energy dissipation characteristics of the ACLD to achieve optimal vibration attenuation.

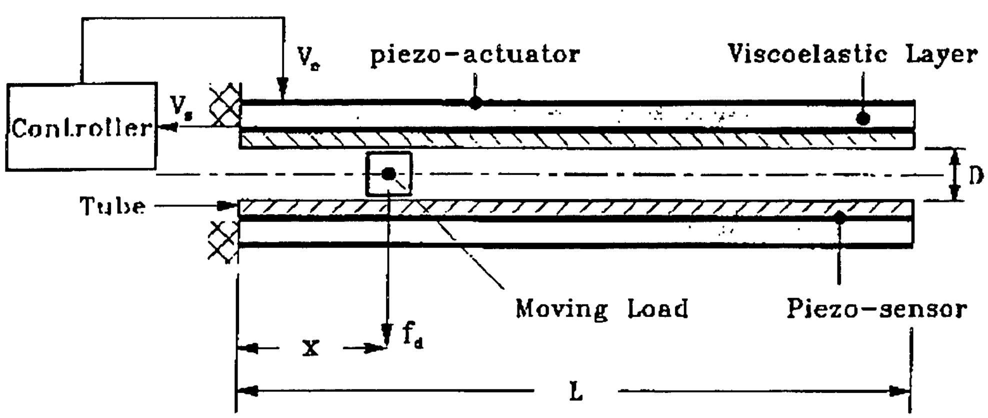


Figure 7. A Tube/ACLD/Moving Load System.

Experimental validation of finite element modeling of the controlled dynamic system is contained within Ro, El-Din, and Baz [15]. The bench-top validation was conducted on a PVC tube (0.405-m long, 0.0142-m bore diameter, 3.62E-3-m thick, 1,769 kg/m^{-3} density), which is fully treated with an ACLD patch as schematically shown in Figure 6. A 34E-3-kg projectile was launched at 500 m/s^{-2}. The thickness of the viscoelastic was 5.08E-4 m with a density of 1,104 kg/m^{-3} (DYAD 606, Soundcoat, NY). The piezoelectric film was very thin, 28E-6 m (Model: 1-1003702-8NiAl, AMP Sensors, Inc., PA).

The muzzle deflections under three operating scenarios are depicted in Figures 8 and 9. The scenarios depict the effect of the derivative feedback control gain upon the ensuing launch dynamics during and immediately following launch. Significant reduction in exit deflection (30%) demonstrates that the method may reduce flexure during launch, although the speed of the bench-top system is slow, even by scale. Employed to attenuate terrain-induced vibrations and subsequently the dynamic initial conditions at launch, the dramatic reduction of homogeneous vibration after shot exit demonstrates the potential viability of the approach.

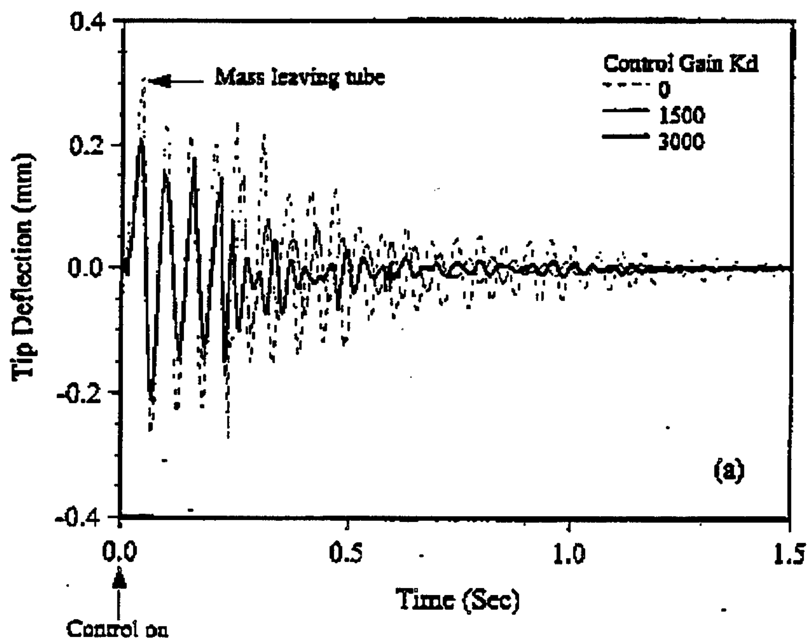


Figure 8. Plot Muzzle Deflection During and After Projectile Exit for Three Control Gain Scenarios.

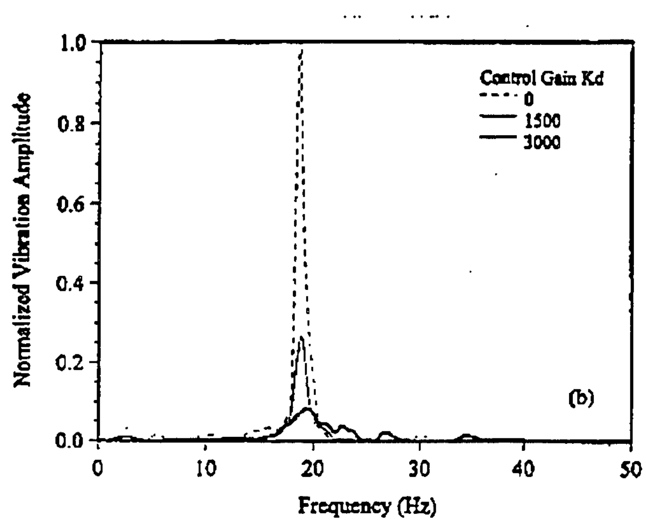


Figure 9. Power Spectral Density for the Same Three Control Gain Scenarios Shown in Figure 8.

It is interesting to note that ACLD does hold some promise toward enhanced in-bore dynamics. Even if the net structural energy removed is small, it may have the potential to modulate the natural gun whip to better time the shot exit with respect to muzzle state and thus reduce the parametric design to disturbance and parametric sensitivity.

6. Conclusions

Hits inflicted upon a close combat system by a near-target during the extended flight time of an indirect weapon, such as a missile, may eliminate it as an asset, regardless of the effectiveness of the indirect weapon's ability to destroy its target. For this reason, the use of a direct-fire gun main armament system is highly desirable for future combat systems. Direct-fire guns, however, must be straight shooters to be effective for near-targets to avoid degraded penetrator performance caused by incident yaw. New bullet design techniques may be insufficient in mitigating exit state linear and angular rates to acceptable levels. The rate at which the yaw of a penetrator damps is a function of the fin assembly, a principal contributor to aerodynamic drag and reduced range. The rate at which the round is translated is a function of the velocity and centerline profile. It is therefore equally important to reduce the gun barrel dynamic contribution to the projectile exit condition that

contributes to yaw. Future efforts will include numerical evaluation of proposed passive dampers using a variety of techniques including the ones detailed in this report.

Limited testing has shown the linear and angular rates to be significant in an EM gun. Fortunately, EM guns offer two distinct planes: the rail plane and the insulator plane. The insulator plane merely guides the projectile, and, indeed, the dispersion in this plane is acceptable. However, the rail plane conducts the current for acceleration through the armature contacts. The mechanical and electric conditions may offer the greatest uncertainty toward dispersion.

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13. ABSTRACT ***(Maximum 200 words)***

In many settings, especially urban warfare, targets may be anticipated to occur very near the weapon platform, or behind concrete walls, much to the hindrance of missiles. Direct guns offer distinct advantages for near-target threats. Nonetheless, both accuracy and performance of long rod penetrators are affected by out-of-plane velocities as well as initial yaw and pitch rates for conventional antitank systems. These components are driven, in part, by the exit conditions of a projectile upon discharge from the launcher. By ignoring cost, logistics, and current technology limitations, these exit conditions may be corrected by smart projectiles, provided the duration of flight is sufficient in length for corrective action. Still, this luxury may not be permissible for near-target performance. It is therefore important in gun design to consider the structural dynamic performance of the launcher system to help mitigate pointing error and angular momentum of rounds upon shot exit. It is the purpose of this report to present emerging technologies relevant to the structural dynamic performance of guns, electromagnetic (EM) or otherwise.

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